

SPIN DEPENDENCE OF DIFFRACTIVE VECTOR MESON PRODUCTION

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I review the recent progress in the theory of s -channel helicity nonconservation (SCHNC) effects in diffractive DIS. SCHNC in diffractive vector meson production is an unique probe of the spin-orbit coupling and Fermi motion of quarks in vector mesons. Photo- and electroproduction of the ϕ and its radial and angular excitations at Jlab is perfectly posed to probe SCHNC in QCD pomeron exchange. I also discuss the unitarity driven demise of the Burkhardt-Cottingham sum rule and large Q^2 & scaling departure from the Wandzura-Wilczek relation.

1 Introduction

The common wisdom is that spin-dependence vanishes in the high energy limit, as an example recall the rapidly decreasing longitudinal spin asymmetry, A_1 , in polarized DIS. In high energy QCD the well known quark helicity conservation was believed universally to entail the s -channel helicity conservation (SCHC) at small x , i.e. the QCD pomeron was supposed to decouple from helicity flip, i.e., spin-dependence of diffractive DIS was supposed to vanish at small x . Here I review the recent work ^{1,2,3,4,5,6,7}, which shows this belief was groundless, and expose an extremely rich SCHNC physics in diffractive DIS at small x . Furthermore, by the virtue of unitarity diffractive SCHNC is found to change dramatically the small- x behaviour of transverse spin asymmetry A_2 and lead to the demise of the Burkhardt-Cottingham sum rule and the departure from the Wandzura-Wilczek relation.

2 Is SCHNC compatible with quark helicity conservation?

The backbone of DIS is the Compton scattering (CS) $\gamma_\mu^* p \rightarrow \gamma_\nu'^* p'$, which at small- x can be viewed as a (i) dissociation $\gamma^* \rightarrow q\bar{q}$ followed by (ii) elastic scattering $q\bar{q}p \rightarrow q\bar{q}p'$ with **exact** conservation of quark helicity and (iii) fusion $q\bar{q} \rightarrow \gamma^*$. The CS amplitude $A_{\nu\mu}$ can be written as $A_{\nu\mu} = \Psi_{\nu,\lambda\bar{\lambda}}^* \otimes A_{q\bar{q}} \otimes \Psi_{\mu,\lambda\bar{\lambda}}$ where $\lambda, \bar{\lambda}$ stands for q, \bar{q} helicities, $\Psi_{\mu,\lambda\bar{\lambda}}$ is the wave function of the $q\bar{q}$ Fock state of the photon. The $q\bar{q}$ -proton scattering kernel $A_{q\bar{q}}$ does not depend on, and conserves exactly, the q, \bar{q} helicities. For nonrelativistic massive quarks, $m_f^2 \gg Q^2$, one only has transitions $\gamma_\mu^* \rightarrow q_\lambda + \bar{q}_{\bar{\lambda}}$ with $\lambda + \bar{\lambda} = \mu$. However,

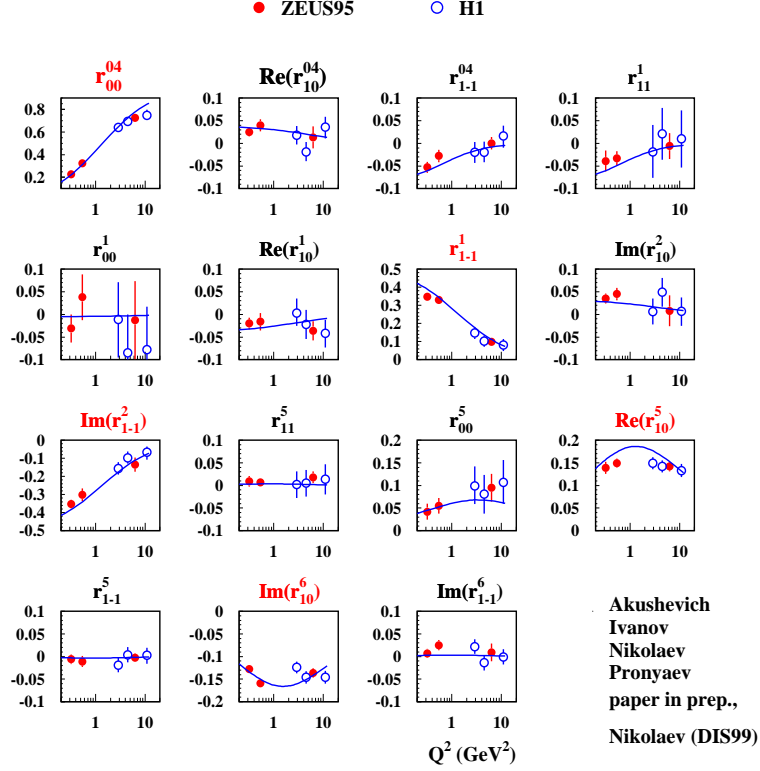


Figure 1: Our prediction ⁵ for the spin density matrix r_{ik}^n of diffractive ρ^0 -meson vs. the experimental data from ZEUS ¹⁰ and H1 ¹¹.

the relativistic P-waves give rise to transitions of transverse photons γ_{\pm}^* into the $q\bar{q}$ state with $\lambda + \bar{\lambda} = 0$ in which the helicity of the photon is transferred to the $q\bar{q}$ orbital angular momentum. Consequently, the SCHNC transitions $\gamma_{\pm}^* \rightarrow (q\bar{q})_{\lambda+\bar{\lambda}=0} \rightarrow \gamma_L^*$ and $\gamma_{\pm}^* \rightarrow (q\bar{q})_{\lambda+\bar{\lambda}=0} \rightarrow \gamma_{\mp}^*$ are allowed ^{8,1,2}. Furthermore, the SCHNC and SCHC amplitudes, which were first calculated in ⁸ and called Φ_1 and Φ_2 there, respectively, have similar x -dependence, i.e., the QCD pomeron exchange contributes to the both SCHC and SCHNC transitions. We emphasize that the above argument for SCHNC does not require applicability of pQCD.

By conservation of the angular momentum the single-flip $T \rightarrow L$ and double-flip $\pm \rightarrow \mp$ transition amplitudes are $\propto \Delta$ and $\propto \Delta^2$, respectively. Here Δ is the (γ, γ') and/or (p', p) momentum transfer.

3 LT interference in diffractive DIS into continuum $\gamma^*p \rightarrow p'X$

The first ever direct evaluation¹ of SCHNC effect in QCD - the LT-interference of transitions $\gamma_L^*p \rightarrow p'X$ and $\gamma_\pm^*p \rightarrow p'X$ into the same continuum diffractive states X - has been reported in 1997 and went unnoticed. Experimentally, it can be measured at HERA by both H1 and ZEUS via azimuthal correlation between the (e, e') and (p, p') scattering planes. The detailed discussion of this asymmetry A_{LT} and its use for the determination of the otherwise elusive $R = \sigma_L/\sigma_T$ for diffractive DIS is found in². Here I only recall that azimuthal asymmetry is the twist-3 effect,

$$A_{LT} \propto \frac{\Delta}{Q} g_{LT}^D(x_{\mathbf{IP}}, \beta, Q^2), \quad (1)$$

where g_{LT}^D is the scaling structure function. It does not decrease at $x \rightarrow 0$!

4 SCHNC in diffractive $\gamma^*p \rightarrow Vp'$

Evidently, diffractive vector meson production $\gamma^*p \rightarrow Vp'$ is obtained from CS by continuation from spacelike γ^* to timelike V . The azimuthal correlation of the (e, e') and (p, V) planes with the vector meson decay plane, and the in-decay-plane angular distributions of decay products, allow the experimental determination of all helicity amplitudes $A_{\mu\nu}$. The consistent analysis of the S -wave and D -wave states of the vector mesons is presented only in⁴. At small x and within the diffraction cone helicity amplitudes for $\gamma_\mu^* \rightarrow V_\nu$ have the following form^{3,4}

$$A_{\nu\mu}(\bar{x}, Q^2, \Delta) = is \frac{c_V \sqrt{4\pi\alpha_{em}}}{2\pi^2} \exp(-\frac{1}{2} B_{3\mathbf{IP}} \Delta^2) \int_0^1 \frac{dz}{z(1-z)} \int d^2k_\perp \psi(z, k_\perp) \int \frac{d^2\kappa_\perp}{\kappa^4} \alpha_S \cdot I_{\nu\mu}(\gamma^* \rightarrow V) \frac{\partial G(\bar{x}, \kappa^2)}{\partial \log \kappa^2} \quad (2)$$

and are calculable in terms of the gluon structure function of the target proton $G(x, \kappa^2)$ taken at $\bar{x} = \frac{1}{2}x_{\mathbf{IP}} = \frac{1}{2}(Q^2 + m_V^2)/(Q^2 + W^2)$. Here $z, (1-z)$ and \mathbf{k} are the Sudakov lightcone variables of the q and \bar{q} in the vector meson. The typical QCD hard scale is $\bar{Q}^2 = z(1-z)Q^2 + m^2$, where m is the quark mass. To the LL \bar{Q}^2 , i.e., for $\kappa^2 \lesssim \bar{Q}^2$, one finds for pure S -wave mesons

$$I_{0L}^S = -4QMz^2(1-z)^2 \frac{2\kappa^2}{Q^4} \left[1 + \frac{(1-2z)^2}{4z(1-z)} \frac{2m}{M+2m} \right],$$

$$I_{\pm\pm}^S = \frac{2\kappa^2}{Q^4} \left[m^2 + 2k^2(z^2 + (1-z)^2) + \frac{m}{M+2m} k^2(1-2(1-2z)^2) \right]$$

$$\begin{aligned}
I_{\mp\pm}^S &= 4z(1-z)\Delta^2 \frac{k^2}{2Q^4} \left(1 + \frac{6\kappa^2(1-2z)^2}{Q^2} \right) \left[1 + \frac{(1-2z)^2}{4z(1-z)} \frac{2m}{M+2m} \right] \\
I_{0\pm}^S &= -2Mz(1-z)(1-2z)^2 \Delta \frac{2\kappa^2}{Q^4} \left[1 + \frac{(1-2z)^2}{4z(1-z)} \frac{2m}{M+2m} \right], \\
I_{\pm L}^S &= -2Qz(1-z)(1-2z)^2 \Delta \frac{2\kappa^2}{Q^4} \frac{2k^2}{Q^2} \frac{M}{M+2m}, \tag{3}
\end{aligned}$$

where M is an invariant mass of the $q\bar{q}$ pair. No separation of the S and D -wave has been done in ⁷.

First, notice how the transverse and longitudinal Fermi motion of quarks in vector mesons are necessary for helicity flip and SCHNC, which would suppress SCHNC in production of heavy quarkonia in which quarks are nonrelativistic. Second, apart from the double-helicity flip, $I_{\nu\mu}^S \propto \kappa^2$ which after the κ^2 integration leads to pQCD calculable $A(\bar{x}, Q^2, \Delta) \propto G(\bar{x}, \sim \frac{1}{4}(Q^2 + m_V^2))$. Third, for the double-helicity flip $A_{\mp\pm}(\bar{x}, Q^2, \Delta) \propto G(\bar{x}, \mu_G^2)$ where $\mu_G^2 \sim (0.5-1)\text{GeV}^2$ and it is not pQCD calculable at any large Q^2 . Finally, by exclusive-inclusive duality ⁹ the above results for $I_{\mu\nu}^S$ can be related SCHNC LT interference in diffractive DIS into continuum ^{1,2} and indeed the dominant SCHNC effect in vector meson production is the interference of production of longitudinal vector mesons by (SCHC) longitudinal and (SCHNC) transverse photons, i.e., the element r_{00}^5 of the vector meson polarization density matrix. The overall agreement between our theoretical estimates ⁵ of the spin density matrix r_{ik}^n for diffractive production of the ρ^0 and the ZEUS ¹⁰ and H1 ¹¹ experimental data is very good. More theoretical analysis of the sensitivity to the wave function of vector mesons is called upon.

5 Sensitivity of SCHNC to spin-orbit coupling in vector mesons

Production of D -wave vector mesons nicely demonstrates a unique sensitivity of helicity flip in $\gamma^*p \rightarrow Vp'$ to spin-orbit coupling ^{3,4}:

$$\begin{aligned}
I_{0L}^D &= -\frac{Q}{M} \cdot \frac{32\mathbf{r}^4}{15(M^2 + Q^2)^2} \cdot \left(1 - 8\frac{M^2}{M^2 + Q^2} \right) \kappa^2, \\
I_{\pm\pm}^D &= \frac{32\mathbf{r}^4}{15(M^2 + Q^2)^2} \cdot \left(15 + 4\frac{M^2}{M^2 + Q^2} \right) \kappa^2, \\
I_{\pm L}^D &= -\frac{24\Delta Q}{M^2 + Q^2} \frac{32\mathbf{r}^4}{15(M^2 + Q^2)^2} \cdot \frac{24Q}{M^2 + Q^2} \kappa^2, \\
I_{L\pm}^D &= \frac{8\Delta}{M} \frac{32\mathbf{r}^4}{15(M^2 + Q^2)^2} \cdot \left(1 + 3\frac{M^2}{M^2 + Q^2} \right) \kappa^2,
\end{aligned}$$

$$I_{\pm\mp}^D = \Delta^2 \cdot \frac{32\mathbf{r}^4}{15(M^2 + Q^2)^2} \cdot \left(1 - \frac{96}{7} \frac{\kappa^2 \mathbf{r}^2}{M^2(M^2 + Q^2)}\right), \quad (4)$$

where $4r^2 = M^2 - 4m^2$. In the D -wave state the total spin of $q\bar{q}$ pair is predominantly opposite to the spin of the D -wave vector meson. As a results, in contrast to S -wave states there is no nonrelativistic suppression of helicity flip. Such an enhancement of SCHNC may facilitate the D -wave vs. $2S$ -wave assignment of the $\rho'(1480)$ and $\rho'(1700)$ and of the $\omega'(1420)$ and $\omega'(1600)$, which remains one of hot issues in the spectroscopy of vector mesons. Notice abnormally large higher twist corrections. For instance, A_{0L} , and LT interference thereof, changes the sign at $Q^2 \sim 7m_V^2$. The ratio $R^D = \sigma_L/\sigma_T$ has thus a non-monotonous Q^2 behavior and $R^D \ll R^S$. Furthermore, $R^D \lesssim 1$ in a broad range of $Q^2 \lesssim 225m_V^2$.

6 SCHNC physics at Jefferson Lab

Above we focused on SCHNC in QCD pomeron exchange which is described in pQCD by a generalized two-gluon ladder in the t -channel. There will be a substantial secondary reggeon contribution to diffractive ρ^0 and ω^0 production at CEBAF energies even after energy upgrade. In pQCD the reggeon exchange is modeled by generalized quark-antiquark ladder in the t -channel¹². An exhaustive analysis of SCHNC for secondary reggeons has not been carried out yet. Still, the above predictions of SCHNC are fully applicable to, and can be tested in, the hidden-strangeness ϕ^0 and radial and angular-excited ϕ' diffractive photo- and electroproduction at CEBAF, because secondary reggeons do not contribute to the ϕ^0 production. Recall, for instance, the Zweig rule.

7 Dramatic impact of SCHNC diffraction upon the small- x behaviour of transverse spin structure function g_2

The transverse spin asymmetry in polarized DIS is proportional to the amplitude of forward CS $\gamma_L^* p \uparrow \rightarrow \gamma_T^* p \downarrow$. This CS amplitude and the transverse spin asymmetry are proportional to $g_{LT} = g_1 + g_2$. Because the photon helicity flip is compensated by the target proton helicity flip, the familiar forward zero of this helicity amplitude is lifted. However, in the standard two-gluon t -channel tower approximation the cross-talk of the target and beam helicity flip is only possible if in the Gribov-Lipatov decomposition of the gluon propagator only one of the gluons is having the nonsense polarization whereas the second one has the transverse polarization. The price one pays for such a combination of polarizations of gluons is the suppression of small- x behaviour of g_{LT} by the

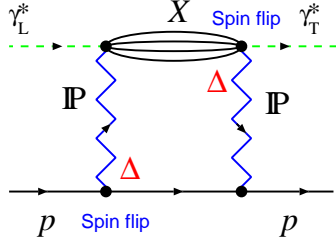


Figure 2: The unitarity diagram for diffractive contribution to g_{LT} .

extra factor $\sim x$ compared to the pomeron exchange in which the both gluons have the nonsense polarization .

The more familiar argument for the vanishing A_2 has been the parton model Wandzura-Wilczek relation between g_{LT} and g_1 ¹³:

$$g_{LT}(x, Q^2) = \int_x^1 \frac{dy}{y} g_1(x, Q^2),$$

which entails that $A_2 \sim A_1$. Because the diffractive pomeron exchange does not contribute to g_1 , the WW relation can be reinterpreted as a vanishing pomeron exchange contribution to g_{LT} . This vanishing of the pomeron contribution has been the principal motivation behind the much discussed Burkhardt-Cottingham ¹⁴ (BC) sum rule $\int_0^1 dx g_2(x, Q^2) = 0$. Our recent discovery is that diffractive SCHNC destroys the both WW relation and BC sum rule ⁶.

The opening of diffractive DIS channels affects, via unitarity, the Compton scattering amplitudes. In ⁶ we have shown how diffractive LT interference in conjunction with spin-flip pomeron-nucleon coupling r_5 give rise to the transverse spin asymmetry $A_2 \propto x^2 g_{LT}$ which does not vanish at small x . The building blocks of the unitarity diagram shown in fig. 2 are the diffractive amplitudes $\gamma^* p \rightarrow p' X$ in which there is a helicity flip sequence, $\gamma_L^* \rightarrow X_L \rightarrow \gamma_T^*$ in the top blob and helicity flip sequences either $p \uparrow \rightarrow p' \uparrow \rightarrow p \downarrow$ or $p \uparrow \rightarrow p' \downarrow \rightarrow p \downarrow$ in the bottom blob. The both amplitudes are proportional to Δ and vanish in the forward direction, but upon the integration over the phase space of $p' X$ one finds the nonvanishing $\int d^2 \Delta \Delta_i \Delta_k$ and unitarity driven transition $\gamma_L^* p \uparrow \rightarrow \gamma_T^* p \downarrow$ which does not vanish in the forward direction. In the old Regge theory language it can be reinterpreted as the two-pomeron cut contribution which for the QCD pomeron has about the same small- x behaviour as the pomeron exchange. The principal difference from the single pomeron

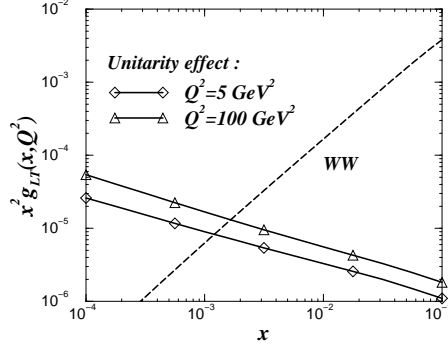


Figure 3: The unitarity correction to, and WW relation based evaluation of, g_{LT} ⁶.

exchange is that the unitarity diagram starts with the four-gluon state in the t -channel and four gluons can furnish the cross-talk of the beam and target helicity flip with pure nonsense polarizations of all the four exchanged gluons.

Our result ⁶ for the diffraction-driven g_{LT} reads

$$g_{LT}(x, Q^2) \propto \frac{1}{x^2} r_5 \int_x^1 \frac{d\beta}{\beta} g_{LT}^D(x\mathbf{P} = \frac{x}{\beta}, Q^2). \quad (5)$$

It rises steeply at small x . It is the scaling function of Q^2 because the diffractive LT structure function $g_{LT}^D(x\mathbf{P}, Q^2)$ is the scaling one. The corresponding transverse spin asymmetry $A_2 \propto x g_{LT}/F_1$ does not vanish at small x , furthermore, at a moderately small x it even rises because $g_{LT}^D(x\mathbf{P}, Q^2) \propto G^2(x\mathbf{P}, \overline{Q}^2)$ where $\overline{Q}^2 \sim 0.5-1$ GeV².

In fig. 3 we show how the steeply rising unitarity correction overtakes at small x the standard g_{LT} evaluated from the Wandzura-Wilczek (WW) relation starting with fits to the world data on g_1 . As such our unitarity effect is the first nontrivial scaling departure from the WW relation

Finally, the above breaking of the WW relation implies $g_{LT} \gg g_1$ and $g_2 = g_{LT}$ at very small x . Consequently, the unitarity-driven rise of g_2 destroys the BC sum rule because the BC integral would diverge severely. Incidentally, the BC sum rule has always been suspect.

Conclusions

The QCD pomeron exchange does not conserve the s -channel helicity. The mechanism of SCHNC is well understood. SCHNC offers an unique window

at the spin-orbit coupling in vector mesons. SCHNC in diffractive DIS drives, via unitarity relation, a dramatic small- x rise of the transverse spin structure function g_2 which breaks the Wandzura-Wilczek relation and invalidates the Burkhardt-Cottingham sum rule. Jlab is perfectly posed to study SCHNC QCD pomeron exchange in photo- and electroproduction of the ϕ and its radial and orbital excitations.

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